

## The LHC p+Pb run from the nuclear PDF perspective

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The p+Pb and Pb+Pb runs at the LHC have opened a possibility to investigate the validity of collinear factorization in a clearly higher center-of-mass energy scale than earlier in nuclear collisions. Indeed, some processes that have been measured routinely in p+p( $\bar{p}$ ) collisions and utilized for years in free proton PDF fits, can now finally be reached also in the nuclear case. Such new data are expected to provide conclusive answers concerning the universality of the nuclear PDFs. In this talk, I will contrast some of the first p+Pb and Pb+Pb measurements to the predictions based on the nuclear PDFs.

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\*Speaker.

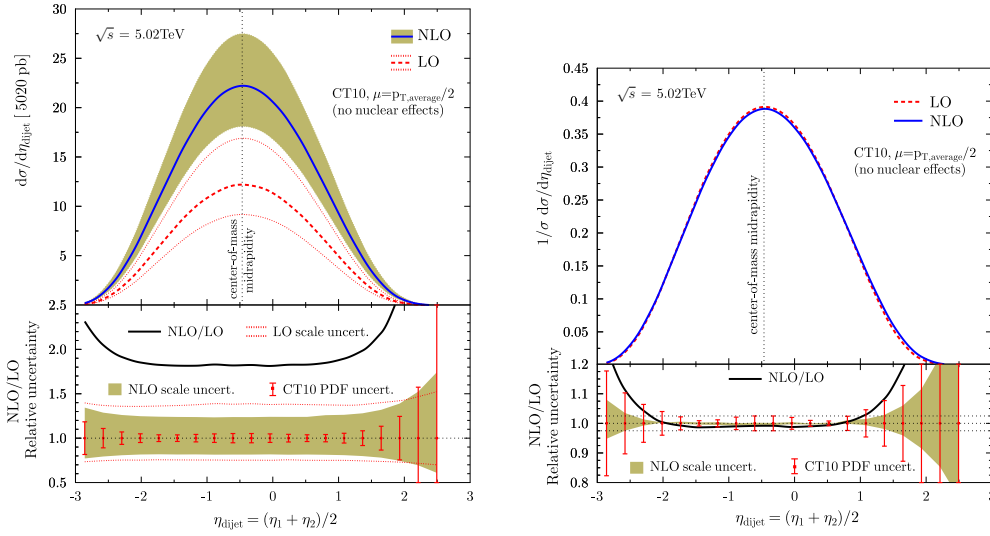
## 1. Introduction

The LHC proton+lead (p+Pb) run with  $\sqrt{s} = 5.02$  TeV and lead+lead (Pb+Pb) runs with  $\sqrt{s} = 2.76$  TeV center-of-mass energy have brought the nuclear collisions to a completely new energy realm. Indeed, before the LHC-era the record energy in nuclear collisions was only  $\sqrt{s} = 0.2$  TeV reached at RHIC-BNL. This increase in center-of-mass energy by more than an order of magnitude has given a possibility to look processes like on-shell heavy gauge boson production and high-transverse-momentum jets that are difficult (or impossible) to measure at RHIC. In this talk I will discuss some of the recent LHC data from nuclear collisions, to what extent they are consistent with the collinear-factorization-based expectations

$$\sigma^{A+B \rightarrow \mathcal{O}} = \sum_{i,j} \underbrace{f_i^A(\mu_{\text{fact}}^2)}_{\substack{\text{nuclear PDFs, obey} \\ \text{the usual DGLAP}}} \otimes \underbrace{\hat{\sigma}^{i+j \rightarrow \mathcal{O}}(\mu_{\text{fact}}^2, \mu_{\text{ren}}^2)}_{\substack{\text{usual pQCD} \\ \text{coefficient functions}}} \otimes \underbrace{f_j^B(\mu_{\text{fact}}^2)}_{\substack{\text{nuclear PDFs, obey} \\ \text{the usual DGLAP}}}$$

whether there is evidence for nuclear modifications in parton distribution functions (PDFs)  $f_i^A$ , and are they consistent with the pre-LHC extractions [1].

## 2. The CMS dijet measurements



**Figure 1:** Predictions for the absolute dijet spectrum (left) and the same distribution normalized by the rapidity-integrated cross section. Figures from [3].

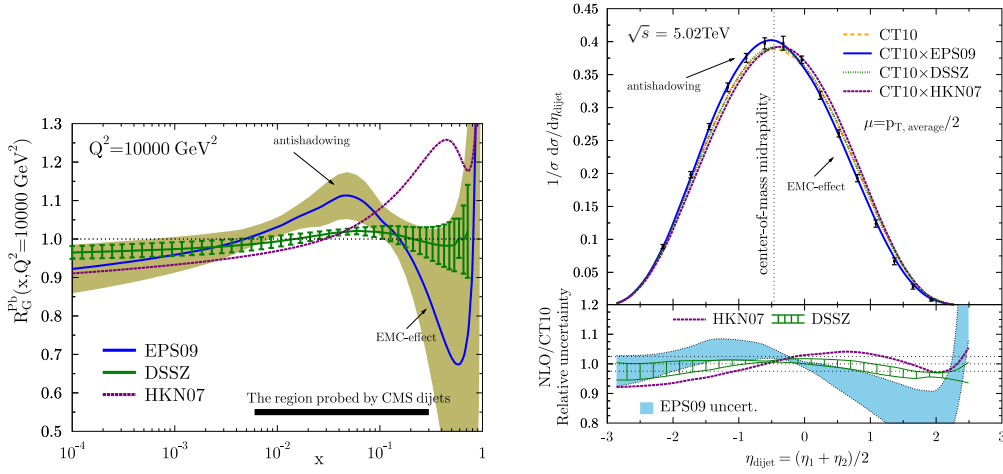
One of the very first data that came out soon after the 2013 p+Pb run was the dijet measurement of the CMS collaboration [2]. The data was presented in bins of dijet “pseudorapidity” ( $\eta_{\text{leading jet}}$  and  $\eta_{\text{sub-leading jet}}$  are the pseudorapidities of the leading and subleading jet)

$$\eta_{\text{dijet}} \equiv \frac{1}{2} (\eta_{\text{leading jet}} + \eta_{\text{sub-leading jet}}), \quad (2.1)$$

with  $p_{T,\text{leading jet}} > 120$  GeV and  $p_{T,\text{sub-leading jet}} > 30$  GeV. At the time of the data taking the proton beam was set to  $E_p = 4$  TeV, and the lead-ions circulated with  $E_{\text{Pb}} = (82/208) \times 4$  TeV  $\approx 1.58$  TeV

correspondingly. For these unequal energies of the colliding nucleons the center-of-mass midrapidity shifted about half a unit in the laboratory frame (indicated in the following figures).

The perturbative QCD calculations [3] for the absolute dijet spectrum at leading order and next-to-leading order (NLO) in strong coupling  $\alpha_s$  are shown in Figure 1 (with no nuclear effects, just using CT10NLO [4]). The NLO correction is always large, almost a factor of two, and the scale uncertainty is around 20% or more for not imposing a lower cut on the dijet invariant mass. All the details of nuclear modifications in PDFs could be easily hidden under such large uncertainties. However, a bit surprisingly, the *shape* of this distribution around the central rapidities does not appear to receive large NLO corrections as demonstrated in the right-hand panel of Figure 1 where the absolute distribution has been normalized by the total cross section. In Figure 2, the preliminary



**Figure 2:** Nuclear modifications in gluon PDFs  $R_G^{\text{Pb}} = g^{\text{Pb}}(x, Q)/g^{\text{P}}(x, Q)$  from different parametrizations and the resulting predictions for the normalized dijet distributions together with the preliminary CMS data.

CMS data [2] for this normalized distribution is compared to the calculations with no nuclear effects (only CT10NLO), and with various nuclear PDFs (nPDFs), HKN07 [5], DSSZ [6] and EPS09 [7]. From these, only EPS09 is capable to systematically reproduce the the data. The reason can be tracked down to the gluon “antishadowing” and “EMC-effect” indicated as well in Figure 2 which are absent in the other parametrizations.<sup>1</sup> As these effects in EPS09 were inferred from RHIC inclusive pion production data at considerably lower center-of-mass energy and much lower transverse momentum ( $p_T < 10\text{GeV}$ ) as well, the agreement here lends support for the conjecture of the nPDF universality.

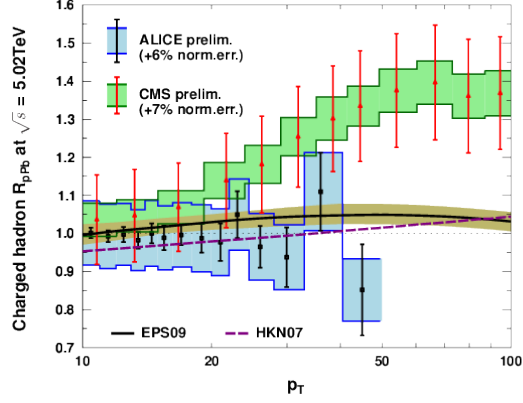
### 3. The dilemma of inclusive charged-hadron production

An issue that has recently caused some confusion is the large enhancement seen in the nuclear modification factor  $R_{p\text{Pb}} \equiv d\sigma_{p+Pb}/d\sigma_{p+p}$  for inclusive high- $p_T$  charged-hadron production reported by the CMS collaboration [9], and shown here in Figure 3. An enhancement as large as this came completely unexpected and is far too large to stem from nuclear modifications in PDFs.

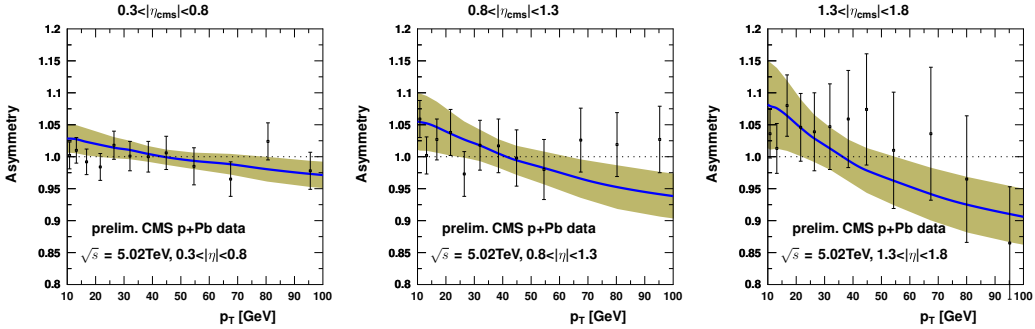
<sup>1</sup>The preliminary nCTEQ parametrization has also similar effects. See Ref. [8] and the talk by A. Kusina, DIS2014.

However, the same observable measured by ALICE [10] shows no sign of such enhancement although the  $p_T$  reach is more restricted than that of CMS. It should be noted that there is no baseline p+p measurement ( $d\sigma_{p+p}$ ) at  $\sqrt{s} = 5.02$  TeV but it has to be constructed by other means to form the nuclear modification factor  $R_{pPb}$ . This could partly contribute to the significant difference between the CMS and ALICE results.

An observable that sidesteps the need for a p+p baseline is the forward-to-backward asymmetry  $d\sigma(\eta_{\text{cms}})/d\sigma(-\eta_{\text{cms}})$  which can be measured by CMS for its wide-enough rapidity acceptance. The results reported in [9] are shown in Figure 4 and compared to the predictions using EPS09. Interestingly, the sizable enhancement seen in Figure 3 appears to be independent of the rapidity interval and these measurements are more or less consistent with the EPS09 predictions.



**Figure 3:** The nuclear modification of inclusive charged-hadron production at midrapidity as measured by ALICE [10] and CMS [9] compared to the nPDF predictions (EPS09 and HKN07).

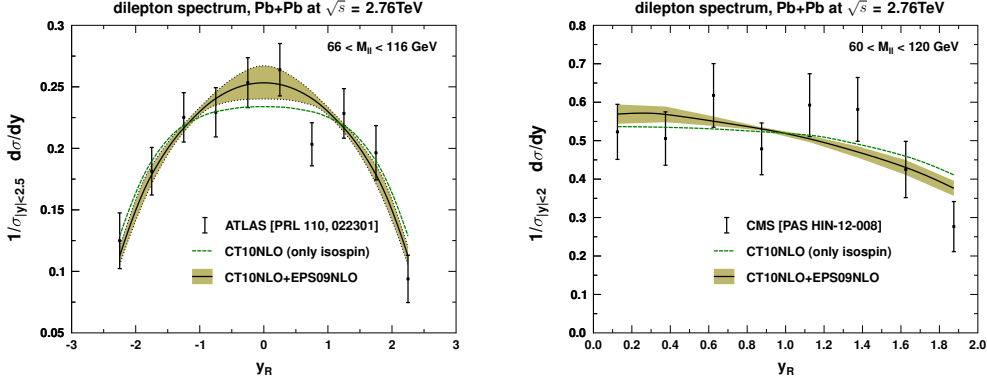


**Figure 4:** Charged-hadron forward-to-backward asymmetry as measured by CMS compared to the EPS09 predictions. Data points taken from [9].

#### 4. Heavy gauge-boson production

Production of charged leptons from heavy gauge-boson decays probes the quark sector of the nPDFs. Theoretically well-understood (e.g. small scale uncertainty, known up to next-to-NLO) observables are the rapidity distributions of opposite-charge di-lepton pairs ( $Z$  production) and single charged leptons ( $W^\pm$  production). The first nuclear data for such observables come from the LHC Pb+Pb collisions at  $\sqrt{s} = 2.76$  TeV center-of-mass energy. While the precision of these Pb+Pb data is not high enough to decide whether we see evidence for the presence of nuclear modifications in PDFs, the data for  $Z$  boson production (shown in Figure 5) and those for the charge asymmetry

in production of  $W^\pm$  bosons (shown in Figure 6) follow very nicely the predictions derived from the collinear factorization.

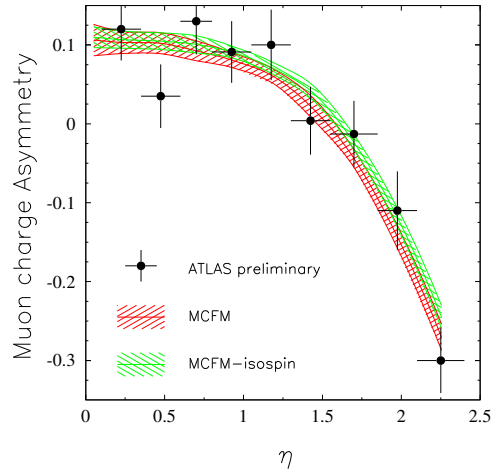


**Figure 5:** The normalized rapidity distribution of Z bosons in Pb+Pb collisions as measured by the ATLAS and CMS collaborations compared to the NLO calculations with and without EPS09 nuclear effects in CT10NLO PDFs. The data points have been obtained from [12, 13] and the integrated yields (the normalization factors) have been estimated by summing up the central data values multiplied by the bin widths.

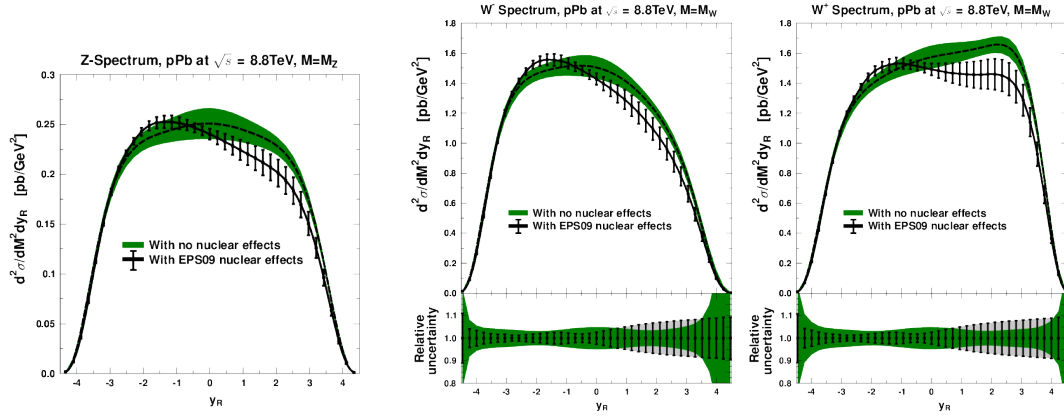
Similarly to the case of dijets discussed earlier, the rapidity distributions of leptons from Z and  $W^\pm$  decays in p+Pb collisions are expected to be different in the proton- and lead-going directions. Examples illustrating what can be generally expected are plotted in Figure 7. As the collected data sample in 2013 p+Pb run is significantly larger than that of the 2011 Pb+Pb run, the precision should consequently be clearly better than the Pb+Pb data shown in Figures 5 and 6. Thus, there is hope that, once available, the p+Pb data for Z and  $W^\pm$  production should provide constraints for the nPDFs.

## 5. Summary

In summary, I have presented some of the LHC p+Pb and Pb+Pb results from the nuclear PDF perspective. Remarkably, the first p+Pb dijet measurement by the CMS collaboration points towards the existence of gluon antishadowing. If confirmed, this would be in accord with the inclusive pion data measured at RHIC. The inclusive minimum-bias charged-hadron production has been measured both by CMS and ALICE and there is a clear inconsistency between these two independent measurements. This underscores the importance to carry out p+Pb measurements in all major LHC experiments to be able to cross-check results. The Z and  $W^\pm$  production have a high



**Figure 6:** The charge asymmetry in Pb+Pb collisions as measured by ATLAS [14] compared to calculations with (red band) and without (green band) EPS09 nuclear effects. Figure by P. Zurita.



**Figure 7:** Illustrative examples of the predicted  $Z$  and  $W^\pm$  rapidity distributions in p+Pb collisions at the LHC and the expected impact of the nuclear modifications in PDFs. Figure from [11].

potential to provide novel constraints for the nuclear quarks. Even in Pb+Pb collisions the collinear factorization appears to work rather well for these processes and the expectations with respect to the upcoming p+Pb data can thus be set high.

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